GEOTHERMAL TRAINING PROGRAMME
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ENVIRONMENTAL IMPACT OF GEOTHERMAL DEVELOPMENT IN THE ÍSAFJARDARBAER AREA, NW-ICELAND

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ABSTRACT

Environmental impact assessment is a powerful environmental safeguard in the project planning process and helps public officials make proper decisions. Today environmental aspects of geothermal development are receiving increasing attention with a shift in attitudes towards the world's natural resources. More and more countries have applied the environmental impact assessment process for geothermal development. The Ísafjardarbaer area is located in NW-Iceland outside the active volcanic and rift zones, where low-temperature geothermal areas predominate. Three geothermal fields are known or postulated, Laugar, Lásvík and Gil. The geothermal fluid temperature is below 70°C. The geothermal water is suited for direct-use. To date, two geothermal production wells have been drilled in the Laugar geothermal field, near Sudureyri, used for space heating and a swimming pool for local residents. The installed capacity is about 2 MWt. A good prospect is in the outer Tungudalur valley, west of Ísafjördur town and, close to it. Two geothermal wells will probably be drilled there, to be used for space heating. The geothermal water would be transferred from the wells through a pipeline to a heating station in Ísafjördur town and then to the houses. The geothermal development may have some negative effects on the environment, such as surface disturbances, and negative effects on vegetation and wildlife due to land use and noise.

1. INTRODUCTION

Geothermal energy is generally accepted as being an environmentally benign energy source, particularly when compared to fossil fuel energy sources. Geothermal development in the last 40 years, however, has shown that it is not completely free of adverse impacts on the environment. Today the environmental aspects of geothermal development are receiving increasing attention with a shift in attitude towards the world's natural resources. Not only is there greater awareness of the effect of geothermal development on the surrounding ecosystems and landscape, but there is also a growing appreciation of the need for efficient and wise use of all natural resources. The purpose of this paper is to use the Environmental Impact Assessment method to study the environmental impact of possible geothermal development in the Ísafjardarbaer area. Figure 1 shows the location of the study area.

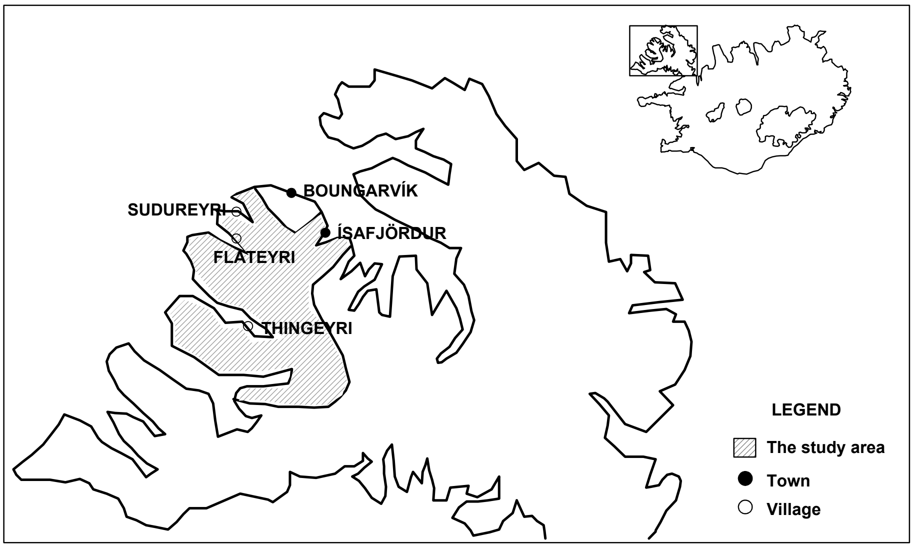

FIGURE 1: The location of the study area

2. ENVIRONMENTAL IMPACT ASSESSMENT

2.1 Introduction

Since the first environmental impact assessment system was established, environmental impact assessment (EIA) has become a powerful environmental safeguard in the project planning process. In recent years there has been a remarkable growth in interest in environmental issues, sustainability and improved management of development in harmony with the environment. More and more countries have set up their own environmental impact assessment systems. Some national and international organizations or legislatives, such as the World Commission on Environment and Development, that espoused the principle of sustainable development in its report of 1987, have proposed procedures; the United Nations Conference on Environment and Development of 1992 established an objective to adapt human activities to nature's carrying capacity (Morris and Therivel, 1995) and seek to influence the relationship between development and the environment. Today, environmental impact assessment is the tool most widely used in environmental management and its objective is to determine the potential environmental, social and health effects of a proposed development in order to provide decision-makers with an account of the implications of a proposed course of action before a decision is made.

2.2 The process of environmental impact assessment

Environmental impact assessment is often considered a process which combines both a procedure to ensure that appropriate projects are subjected to an environmental impact assessment with results that influence the planning and execution of a project, and a method for analyzing and assessing the effects of a proposal on environmental systems and the quality of the environment (Thors and Thóroddsson, 2001). The general stages are:

1. Project screening;
2. Scoping;
3. Consideration of alternatives;
4. Description of the project or development;
5. Description of the environmental baseline;
6. Identification of key impacts;

7. The prediction of impacts;
8. Evaluation and assessment;
9. Public consultation;
10. Environmental impact statement presentation;
11. Decision-making;
12. Review;
13. Post-decision monitoring;
14. Auditing following monitoring.

In Iceland, an environmental impact assessment of a project and its operating license are processed at the same time; however, development permission should be in accordance with the environmental impact assessment decision. The generalized environment impact assessment process is: Screening → scoping → baseline studies → impact prediction → impact evaluation → reporting → review → decision → monitoring.

2.3 Methods of environmental impact assessment

Various environmental impact assessment methods have been developed. They are used at various stages in the environmental impact assessment process and the aim of all of them is to give an overview of all possible environmental impacts associated with a particular project and a way to evaluate the significance of a particular impact. The methods most commonly used are checklists, matrices, networks and overlay maps.

2.4 Environmental regulations

Most countries have embodied their environmental concerns in legislation and regulations. These regulations are remarkably similar, and many countries have regulations that require an environmental analysis of a proposed geothermal project, as well as specific regulations that define the quantities of pollutants that may be emitted to the atmosphere or discharged to land and water. There is, however, a significant variation in the number of agencies involved in the environmental review of a project, and the amount of time required from application through to project approval. The different types of geothermal fields and geothermal development have varying impacts and legislation needs to cover all possible development scenarios. In general, as development proceeds, the legislative requirements move from environmental impact reports during the pre-development stage, to gaining consents for the development and finally a monitoring role during production. The US, Philippines, New Zealand and European Community have relevant environmental regulations. Geothermal energy production generally has a well-deserved image as an environmentally friendly energy source when compared with fossil fuels and nuclear energy. Continuing justification for this reputation will rely as much on the conscience of the developer as on the underlying legislation.

Environmental impact assessments (EIA) in Iceland have been carried out since May 1994. The law based on EC Directive 1985-11/1997, is the *Law on environmental impact assessment in Iceland* from the year 2000 (Planning Agency, 2001). The Ministry of Environment is the principal authority in the field covered by this Act, and the Planning Agency consults the minister and is responsible for the supervision of the implementation of the Act and providing guidelines. The Planning Agency decides on the environmental impact assessment and also decides whether developments should be made subject to environmental impact assessment.

In this law, it is stipulated that all projects, which may have significant effects on the environment, on the ground, within territorial waters, within territorial air or in the pollution territory of Iceland, should be made subject to environmental impact assessment. The following projects should be always subject to environmental impact assessment:

- Hydropower: > 10 MWe, 3 km^2;
- Geothermal: > 50 MWt installed power for direct use, 10 MWe for power production;
- Power lines: > 66 kV;
- Roads: > 10 km;
- Gravel mines: > 50,000 m^2, or > 150,000 m^3;
- Chemical plants;
- Disposal of hazard waste and household waste, etc.

So far 110 projects have been subjected to environmental impact assessment (EIA) in Iceland, more than 50% being road projects. Six geothermal projects have been subjected to EIA. The nature of the projects and the results of the assessments or the present status are listed in Table 1.

TABLE 1: The nature of the projects and the results of the assessments or the present status (Planning Agency, 2001)

Location	Project	Year of decision	Status
Ölkelduháls	Drilling of an exploration well	1994	Project conditionally approved. Appeal led to change in road location. Well drilled.
Reykjanes	Utilization of the geothermal area	2000	Conditionally approved. New assessment plan with reduced activity has been published.
Graendalur	Drilling of an exploration well.	2000/2001	Well at mouth of valley conditionally approved, well 2.2 km inside valley rejected. Decision on appeal from developers to the Ministry of Environment rejected.
Bjarnarflag-Námafjall	40 MWe power plant with a 132 kV power line to Krafla	2000	Further assessment required; work underway to comply with that.
Nesjavellir	Increasing size of power plant from 76 MWe to 90 MWe	2001	Project approved.
Krafla	Increasing size of power plant from 60 MWe to 100 MWe		Assessment plan approved. EIR published and public meeting already held. Deadline for appeals Oct. 21., 01. Decision pending.

2.5 Criteria and guidelines (World Bank, 2001)

Most countries have developed or adopted criteria to protect their own environment. The criteria may be designed to specifically protect native species or ecosystems, or may be adopted from those of another country with similar biological characteristics. There are key sets of criteria on which most others are at least partially based, such as for

- Air quality;
- Drinking water protection;
- Aquatic life protection;
- Stock watering and irrigation.

The most recent compilations of these are by The US Environmental Protection Agency (US EPA), The Water Research Council (WRC), Australian and New Zealand Environment Conservation Council (ANZECC), The Canadian Council of Resource and Environment Ministers (CCREM), and The World Health Organization (WHO).

3. GEOTHERMAL DEVELOPMENT

3.1 Introduction

Iceland is situated on the Mid-Atlantic Ridge, which marks the rifting plate boundary between the Eurasian and the North-American plates. When the plates drift apart, the gap between them is constantly filled with extrusive and intrusive igneous rocks. At present, a highly active volcanic zone runs across Iceland from southwest to northeast, from the Reykjanes peninsula in the southwest to the Mývatn-Öxarfjördur area in the northeast. The main structure of the geology of Iceland is shown in Figure 2 (Fridleifsson, 1979).

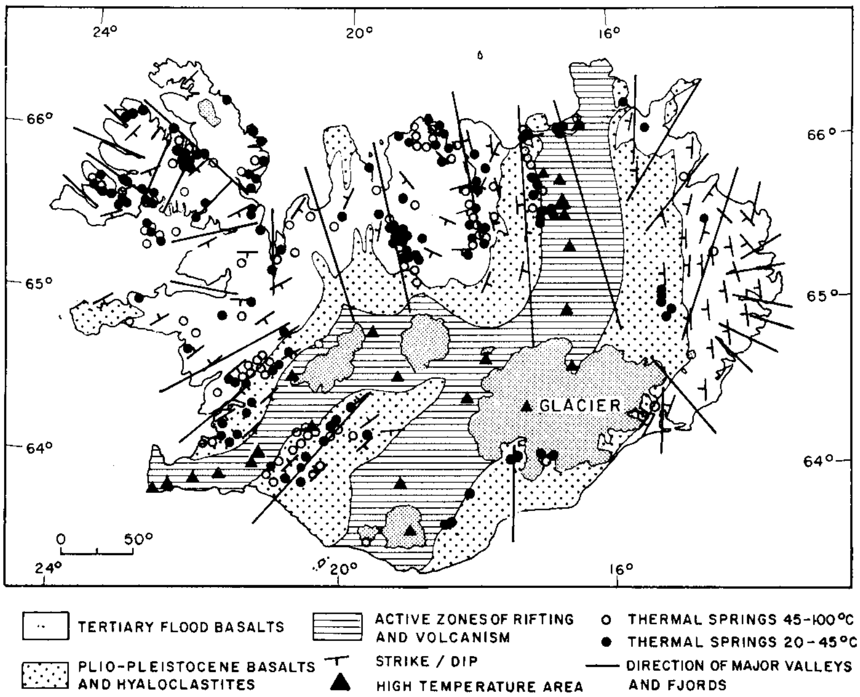

FIGURE 2: A geological map of Iceland (Fridleifsson, 1979)

The high-temperature areas typically reach more than 200°C temperature at 1 km depth. They are only found within the volcanic rift zone. The concentration of geothermal activity within the volcanic rift zone is at least partly due to intrusive activity in volcanic systems and their associated high-temperature areas. The volcanic rift zone is characterized by highly porous unaltered lava in the uppermost 0.5-1 km and numerous active faults and open fractures. Therefore all heat transfer within the rift zone is by active water flow and it is not possible to measure a gradient there, at least not in the uppermost 0.5-1 km.

The low-temperature areas are found mainly outside the volcanic rift zone. The temperature is usually lower than 150°C at 1000 m depth within the geothermal systems. They are quite abundant on the west side of the volcanic rift zone but scarce on the east side of the rift zone. The low-temperature areas are composed of Plio-Pleistocene and Tertiary volcanic rocks. Due to the oceanic climate precipitation is heavy in the island. Some of the precipitation percolates deep into the bedrock in the highland areas and flows laterally along faults and permeable horizons for distances of tens of kms before it appears on the surface along dykes or faults in the lowland. The water withdraws heat from the regional heat flow during its passage through the strata.

Ísafjardarbaer lies in NW-Iceland where only low-temperature activity is found. The bedrock was formed about 13 to over 15 million years ago. It consists of a 1200-1800 m thick sequence of basalt lava flows with interbedded sediments. The strata dip gently, 3-6° at sea level, to the southeast. The average accumulation rate of the lower part of the lava pile in the northwest peninsula has been estimated to be of the order of 0.7 km per million years (Gudmundsson, 1991).

3.2 Status of geothermal development

Since the 1960s more than 60 wells have been drilled in this area for gradient measurement, exploration and production. Figure 3 shows the location of geothermal wells in the study area. Table 2 summarizes well locations, depth and temperature. LA-02 and LA-05 located in the Laugar geothermal field near Sudureyri are used for space heating and a swimming pool. The temperature of LA-02 is 67˚C and the depth is 648 m. The temperature of LA-05 is 59˚C and the depth is 1140 m. The capacity of the field is about 2 MWt (Ragnarsson, 2000).

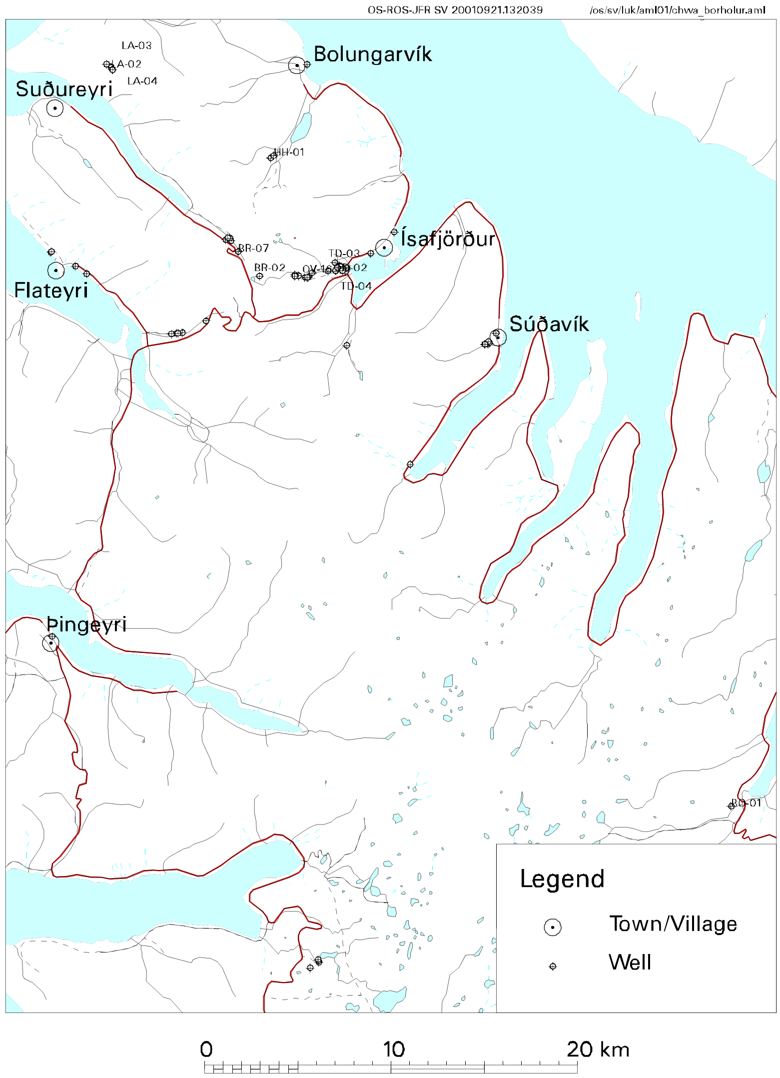

FIGURE 3: The distribution of geothermal wells in the study area

3.3 Geothermal development in the future

The Lindal diagram (Líndal, 1973; Gudmundsson et al., 1985) (Figure 4) indicates temperature ranges suitable for various geothermal uses. Typically, the agricultural and aquacultural uses require the lowest temperatures, from 25 to 90˚C. The amounts and types of chemicals such as arsenic and dissolved gases are a major problem with plants and animals, thus heat exchangers are often necessary. Space heating requires temperatures in the range 50-100˚C, with 40˚C useful in some marginal cases and ground source heat pumps extending the range down to 4˚C. Cooling and industrial processing normally require temperatures over 100˚C. The study area has a potential for low-temperature geothermal utilization. The temperature would be below 70˚C, so it could be used for space heating, animal husbandry, soil warming and fish industry.

Tunga area lies west of Ísafjördur town and close to the town. More than 20 gradient wells have been drilled there from the 1970s to now. Every well's temperature has been measured and the geothermal gradients calculated. Figure 5 (Karlsdóttir and Saemundsson, 1998) shows the distribution of the geothermal gradient in the area. Through analysis of geothermal gradients, geothermal water may be discovered in this area. So a probable geothermal development scenario is for two geothermal wells being drilled in this area to provide heat for the town's residents. The geothermal water is taken from wells and transferred to a central heating station through a pipeline, then to the houses through existing pipelines. Figure 6 shows the possible well locations and the path along which pipeline would be built. The wells are located in a valley, there is a main road through the valley. So a new road is not necessary, just a path from the main road to the well location. The pipeline would be built along the road.

TABLE 2: Data on some geothermal wells in the study area

Name	Location	Depth (m)	Temperature (˚C)	Name	Location	Depth (m)	Temperature (˚C)
TD-01	Tunga	114.1	17.3	OV-20	Tunga	150	29.9
TD-02	Tunga	950	52.8	OV-21	Tunga	102	15.7
TD-03	Tunga	965	53.4	OV-22	Tunga	102	15.5
TD-04	Tunga	1246.2	60.4	OV-23	Tunga	100	17.8
OV-03	Skutulsfjördur valleys	131.5	10.7	OV-24	Tunga	102	16.2
OV-04	Skutulsfjördur valleys	101.5	9.4	OV-25	Tunga	135.5	19.1
OV-05	Tunga	133	21.5	OV-26	Tunga	110	17.1
OV-06	Ísafjördur	130	13.6	OV-27	Tunga	100	19.5
OV-07	Ísafjördur	101.5	10.8	OV-28	Tunga	135	23.6
OV-08	Tunga	101.5	11.6	OV-30	Tunga	135	21.4
OV-09	Tunga	138	18.1	BR-01	Breidadalur	59.5	8.5
OV-10	Fremri-Hnífsdalur	101.5	9.2	BR-02	Breidadalur	59.5	11.9
OV-11	Fremri-Hnífsdalur	138.5	15.3	BR-03	Breidadalur	89.5	9
OV-14	Ísafjördur	100	8.1	BR-04	Breidadalur	59.5	10.1
OV-15	Tunga	144	16.7	BR-05	Breidadalur	57	10.9
OV-16	Tunga	213	32	LA-02	Laugar	648	66.8
OV-17	Tunga	120	24.9	LA-03	Laugar	520	66
OV-18	Tunga	126	22	LA-04	Laugar	404	63.3
OV-19	Tunga	129	25.8	LA-05	Laugar	1140	59

3.4 Possible impacts of geothermal development

Geothermal energy does have some environmental impacts. In most cases the degree to which geothermal exploitation affects the environment is proportional to the scale of such exploitation (Lunis, 1989). For example, the environmental impacts associated with geothermal direct-use projects are often minimal. Those associated with large-scale electrical generation projects may be quite large. The direct- use projects are often designed as closed-loop use systems where the low- or medium-temperature geothermal fluids are circulated through a heat exchanger or a heat pump.

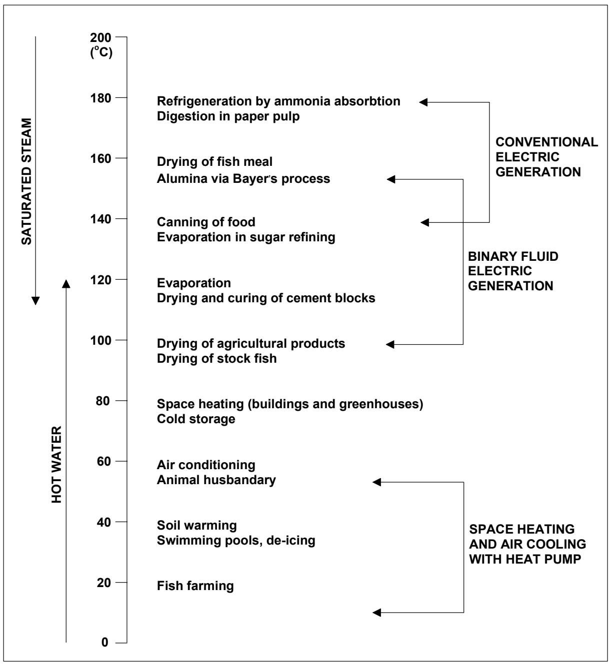

FIGURE 4: The Lindal diagram

The development of a low-temperature geothermal field has many of the same potential environmental problems as that of a high-temperature geothermal field, although they are likely to be far less serious. Careful planning to avoid environmental problems, coupled with appropriate mitigation measures for the problems that cannot be avoided, can bring impacts to acceptable levels. Table 3 summarizes the probability and severity of the effects on the environment of developing geothermal direct-use projects (Dickson and Fanelli, 1995).

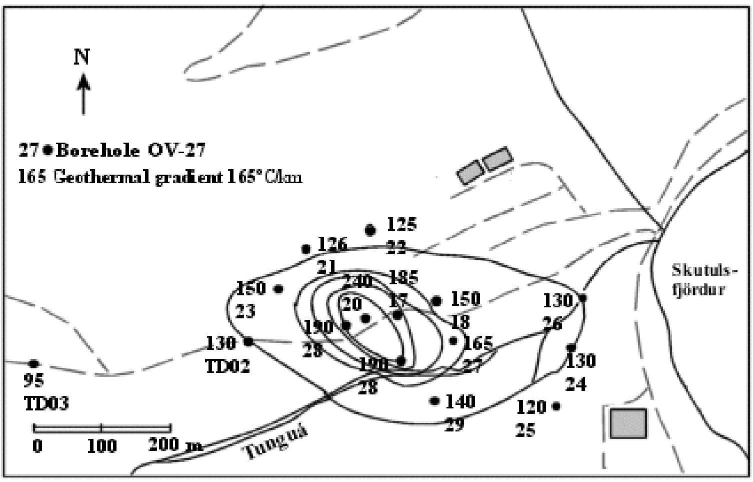

FIGURE 5: Location of boreholes and geothermal gradient in the Tungua area

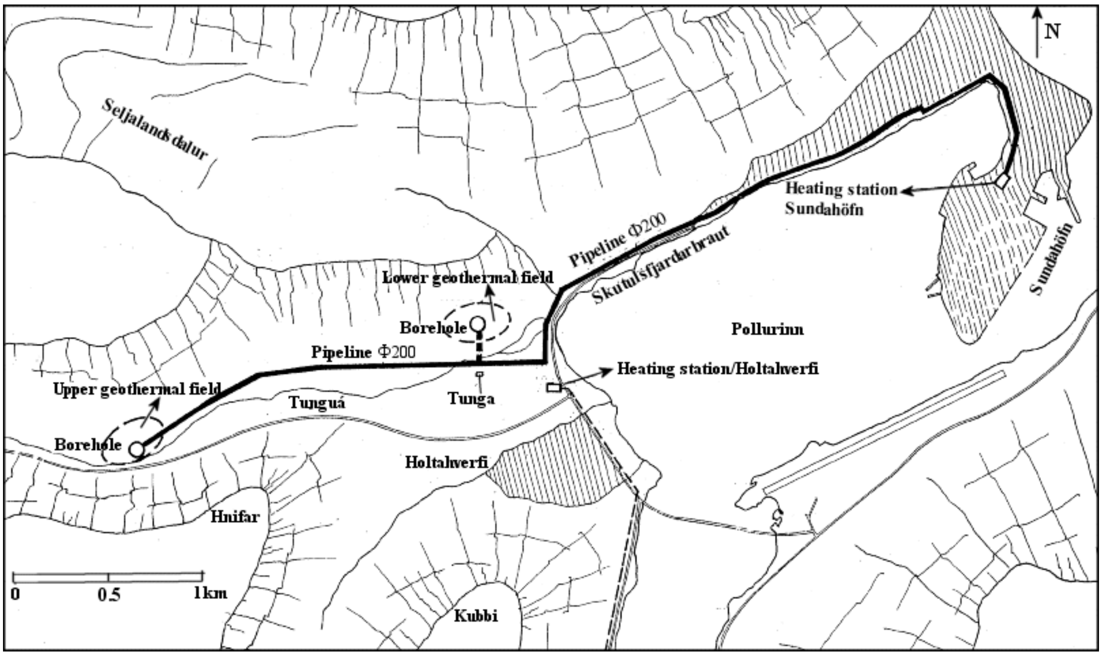

FIGURE 6: Possible sites of boreholes and main pipeline locations in the Ísafjördur area

TABLE 3: Probability and severity of potential environmental impact of direct-use projects

Impact	Probability of occurrence	Severity of consequences
Air pollution	L	M
Surface water pollution	M	M
Underground pollution	L	M
Land subsidence	L	L to M
High noise levels	H	L to M
Well blowouts	L	L to M
Conflicts with cultural and archeological features	L to M	M to H
Social-economic problems	L	L
Chemical or thermal pollution	L	M to H
Solid waste disposal	M	M to H

L=Low; M=Medium; H=High

4. EXISTING ENVIRONMENT

4.1 Landscape

Most of the landscape of the northwest peninsula of Iceland, the West-fjords, is composed of sheer cliffs and mountains with very little soil by the coastline. But there are many plants found on the mountain plateau and in the valleys. The mainland reaches 300-800 m above sea level. The land is indented by a great many fjords, more than half of all the fjords in Iceland, with narrow valleys leading back from the sea. In the north area, around Ísafjördur town, Ísafjardardjúp almost divides the landmass into two. Figure 7 shows the terrain of Skutulsfjördur.

The following description is based on Hjaltason (1949). In Hnífsdalur narrow mountains with steep landslides below dark rocks dominate the landscape. The Hnífsdalur village is in a low by the sea on a small hill from above which a small valley stretches towards the mountains. A river runs along the valley to the sea through the village. The area is barren and sparsely vegetated due to rocks and a dearth of soil. Still, some people have managed to grow meadows and gardens. There is an acute risk of snow avalanches under the tall steep mountains, one of the largest coming in 1910 from Búdarhyrna killing 18 people. A road runs along Eyrarhlíd to Ísafjördur town.

The land on which Ísafjördur town is built used to belong to the farm Eyri in Skutulsfjördur, where there was a church and a rectory. By the middle of the 19th century a small fishing village had been established there which administratively was made a town in 1866 and grew fast until well into the 1900s. Fishing, fish processing, commerce and small industry did and do constitute the livelihood of the inhabitants. The name Ísafjördur for the town is not Icelandic in origin but made up by Danish traders with no local knowledge, who derived it from Ísafjardardjúp (Ísafjördur Bay whose name is derived from the innermost fjord leading from the bay, Ísafjördur). The town is on the west side of Skutulsfjördur on a spit of land extending nearly across the whole fjord to the east from Eyrarhlíd. The innermost part of the fjord is called Pollur and constitutes a very good natural harbour. A steep landslide hill called Gleidarhjalli rises above the town. Further into the fjord than the spit lies the peninsula Torfsnes with a considerable amount of human development, and still further inland is another peninsula, Stakkanes. There is a small hydropower station in Fossar, Engidalur and water for general consumption comes from aquifers inside the road tunnel to Flateyri and Sudureyri.

The Skutulsfjördur valleys extend to the south from the bottom of the fjord. Lowlands are sparse apart from low gravel ridges along the seashore but the mountains are lower than those further out by the fjord. There is more vegetation here and few rocks on the edges until much further inland, in the highlands. The northern- and westernmost reaching valley is Tungudalur extending from the southwest corner of the Pollur. It is vegetated on the west side by quite lush birch bushes, called Tunguskógur wood, a popular area for summer houses. It is a sheltered area and good land for berries. The river Buná runs through it. Further to the northwest and higher up on the mountain there is Seljalandsdalur valley a popular skiing area in winter. At the end of the valley there is the highest mountain in the area, Kistufell (781 m). A little further to the south there are Midfell and Búrfell (741 m) and the pass between them is called Gyltuskard. The next valley to the south is Dagverdardalur through which the river Úlfsá runs. The mountain between the valleys is called Hnífafjall. In the opening of the valley there is a small populated area. To the east of Dagverdardalur there is Engidalur with Fellsháls and Langafell in between. Engidalur is the deepest and most extensive of the valleys and most inviting for settlement compared to other parts of the area (which cannot be regarded as very inviting). The river Langá runs along the valley originating in Thóruskardshjallar. The aforementioned hydropower station is there in the eastern part of the valley, deriving its water power from lakes up on the mountain to the west of the valley.

By the southeast corner of the Pollur is the farm Kirkjuból where there is some lowland at the opening of Engidalur. The hill from there to the east of the fjord is called Kirkjubólshlíd. It is high and steep with grand cliffs and unvegetated landslides. A little further out there is a spit called Skipeyri where the local airport is located. There are two corries in the mountain above Kirkjuból, Kirkjubólshvilft and further out Naustahvilft.

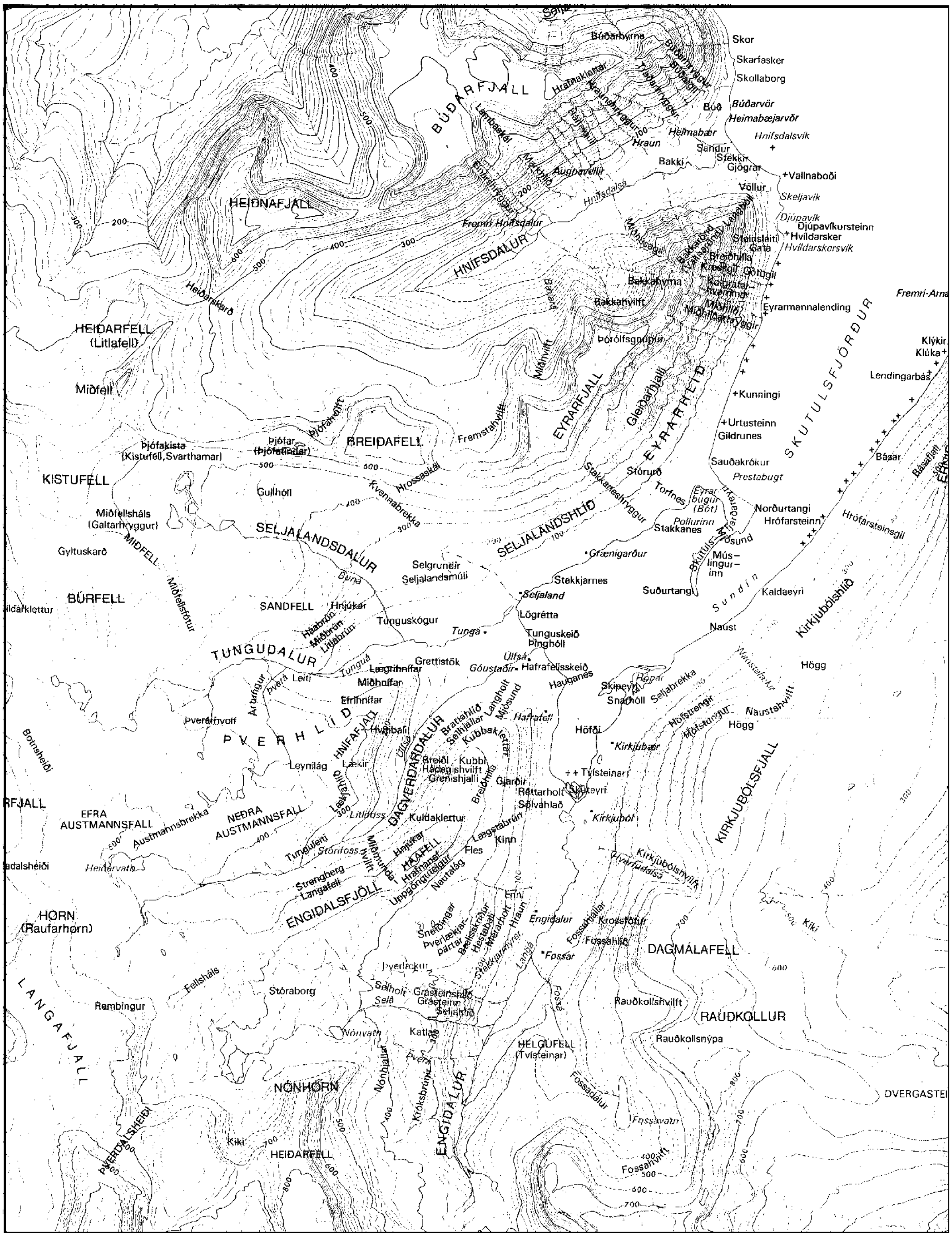

FIGURE 7: Detailed map of Skutulsfjördur and vicinity

4.2 Soil

Erosion intensity in this area reflects that these are highlands with steep hills and scant vegetation. But on the mountain plateau and in the valley, where many plants can be found the erosion degree may be reduced.

Vestur-Bardastrandarsýsla and Ísafjardarsýsla counties are dominated by mountains and wastelands, often 60-70% of the land area. An erosion severity of 3 is common, particularly because there is a lot of scree and soilfluction on vegetated hills. Erosion spots are widespread where the high country is vegetated. Water erosion is also common, as might be expected in such a steep landscape. However, there are a few areas where erosion is considered severe (Arnalds et al., 2001).

4.3 Vegetation

In many respects the vegetation differs from that found elsewhere in Iceland. Some rare plants are found only in the West-fjords, but the special characteristics of the vegetation are first and foremost due to the variety of the landscape, the annual snowfall, and nowadays the fact there is little grazing by livestock.

Birch woods are common, and in many places mountain ash rise up above the low-growing brush. Ash and birch together form inviting woods. The West-fjords are famous for berries. The annual snowfall protects the bilberries and heather and other sensitive plants like dwarf cornel and ferns. The steep hillsides are cut in places by landslides, and grass and heath patches grow on the resulting slopes, together with wooly willow and low-growing birch. Low hills and heaths are covered with plant growth-crowberries and Iceland moss – with mosses dominant in the higher areas and wetlands and ponds in the lower areas. Table 4 shows recorded plants in Engidalur, Dagverdardalur and Tungudalur, Skutulsfjördur (H. Kristinsson, pers. comm.).

TABLE 4: Plants found in Engidalur, Dagverdardalur and Tungudalur

Latin name	English name	Location
Agrostis stolonifera	Creeping bent	Naust Kirkjubólsfjall Skutulsfjördur
Archemilla alpina	Alpine lady´s mantle	Kirkjubólsfjall Skutulsfjördur
Alchemilla filicaulis	Common lady´s mantle	Engidalur Skutulsfjördur
Alchemilla glomerulans	Common lady´s mantle	Dagverdardalur Skutulsfjördur
Alchemilla wichurae	Common lady´s mantle	Kirkjuból Skutulsfjördur Kirkjubólsfjall Skutulsfjördur
Alopecurus geniculatus	Marsh foxtail	Kirkjuból-Brautarholt Skutulsfjördur Dagverdareyri Skutulsfjördur
Angelica sylvestris	Wild angelica	Tunguskógur Skutulsfjördur
Anthoxanthum odoratum	Sweet vernal-grass	Kirkjubólsfjall Skutulsfjördur
Arabis alpina	Alpine rock-grass	Naust Kirkjubólsfjall Skutulsfjördur
Bartsia alpina	Alpine bartsia	Engidalur Skutulsfjördur
Blechnum spicant	Hard fern	Seljalandsdalur
Brassica rapa	Turnip	Ísafjördur-Tungudalur
Bromus arvensis	Field brome	Ísafjördur-Tungudalur
Carex	Sedge	Engidalur Skutulsfjördur
Carex atrata	Black Apine sedge	Engidalur Skutulsfjördur
Carex bigelowii	Stiff sedge	Kirkjubólsfjall Skutulsfjördur
Carex canescens	White sedge	Kirkjuból Skutulsfjördur
Carex capillaries	Hair sedge	Kirkjubólsfjall Skutulsfjördur
Carex dioica	Dioecious sedge	Buná Tungudal Dagverdareyri Skutulsfjördur
Carex echinata	Star sedge	Kirkjuból Skutulsfjördur
Carex glareosa	Gravel sedge	Engidalur Skutulsfjördur
Carex lachenalii	Hare´s-foot sedge	Dagverdareyri Skutulsfjördur
Carex lyngbyei	Lyngbye´s sedge	Engidalur Skutulsfjördur
Carex maritime	Curved sedge	Naust Kirkjubólsfjall Skutulsfjördur
Carex norvegica	Close-headed Alpine sedge	Engidalur Skutulsfjördur Naust Kirkjubólsfjall Skutulsfjördur
Carex pilulifera	Pill edge	Engidalur Skutulsfjördur Kirkjuból-Brautarholt Skutulsfjördur
Carex rufina	Red sedge	Dagverdareyri Skutulsfjördur
Carex vaginata	Sheathed sedge	Kirkjubólsfjall Skutulsfjördur Engidalur Skutulsfjördur
Cerastium alpinum	Alpine mouse-ear	Engidalur Skutulsfjördur
Corallorhiza trifida	Coralroot orchid	Naust Kirkjubólsfjall Skutulsfjördur

Latin name	English name	Location
Dactylorhiza maculata	Heath spotted orchid	Tunguskógur Skutulsfjördur
Deschampsia alpina	Alpine hair-grass	Dagverdardalur Skutulsfjördur
Deschampsia flexuosa	Wavy hair-grass	Engidalur Skutulsfjördur
Diphasiastrum alpinum	Alpine clubmoss	Dagverdardalur Skutulsfjördur Buná Tungudal
Draba incana	Hoary whitlow grass	Tunga Skutulsfjördur
Draba norvegica	Rock whitlow grass	Kirkjubólsfjall Skutulsfjördur
Drosera rotundifolia	Round-leaved sundew	Ísafjördur-Tungudalur
Dryopteris expansa	Northern bucklet-fern	Kirkjubólsfjall Skutulsfjördur
Epilobium anagallidifolium	Alpine willowherb	Dagverdareyri Skutulsfjördur
Epilobium hornemanni	Horneman´s willowherb	Naust Kirkjubólsfjall Skutulsfjördur
Epilobium lactiflorum	Milky willowherb	Kirkjubólsfjall Skutulsfjördur Tunguskógur-Mýri
Erigeron borealis	Alpine fleabane	Engidalur Skutulsfjördur
Festuca rubra	Red fescue	Engidalur Skutulsfjördur
Galium pumilum	Slender bedstraw	Naust Kirkjubólsfjall Skutulsfjördur
Gentianella amarelle	Autumn gentian	Dagverdareyri Skutulsfjördur
Gymnocarpium dryopteris	Oak fern	Dagverdareyri Skutulsfjördur
Hieracium	Hawkweed	Kirkjuból-Brautarholt Skutulsfjördur
Hieracium alpinum	Alpine hawkweed	Kirkjuból Skutulsfjördur
Hieracium elegantiforme	Hawkweed	Seljalandsdalur
Hieracium islandicum	Icelandic hawkweed	Kirkjuból-Brautarholt Skutulsfjördur Kirkjuból Skutulsfjördur
Hieracium stroemfeltii	Hawkweed	Kirkjuból Skutulsfjördur Kirkjubólsfjall Skutulsfjördur Tunguskógur Skutulsfjördur
Hippuris vulgaris	Mare´s tail	Naust Kirkjubólsfjall Skutulsfjördur
Juncus castaneus	Chestnut rush	Kirkjubólsfjall Skutulsfjördur Naust Kirkjubólsfjall Skutulsfjördur Dagverdareyri Skutulsfjördur
Juncus filiformis	Thread rush	Dagverdareyri Skutulsfjördur
Listera ovata	Common twayblade	Kirkjuból-Brautarholt Skutulsfjördur
Luzula arcuata	Curved wood-rush	Naust Kirkjubólsfjall Skutulsfjördur Kirkjubólsfjall Skutulsfjördur
Luzula multiflora	Heath wood-rush	Kirkjubólsfjall Skutulsfjördur
Luzula spicata	Spiked wood-rush	Kirkjubólsfjall Skutulsfjördur
Lycopodium annotinum	Interrupted clubmoss	Kirkjuból Skutulsfjördur Dagverdareyri Skutulsfjördur
Mertensia maritima	Oyster plant	Naust Kirkjubólsfjall Skutulsfjördur
Myosotis stricta	Strict Forget-me-not	Seljaland Skutulsfjördur
Omalotheca supina	Dwarf cudweed	Kirkjubólsfjall Skutulsfjördur Dagverdareyri Skutulsfjördur
Omalotheca sylvatica	Heath cudweed	Tunga Skutulsfjördur
Orthilia secunda	Wintergrass	Kirkjuból-Brautarholt Skutulsfjördur Kirkjuból Skutulsfjördur
Papaver radicatum	Arctic poppy	Dagverdardalur Skutulsfjördur
Phleum alpinum	Alpine cat's-tail	Dagverdardalur Skutulsfjördur
Plantago maritime	Sea plantain	Kirkjuból Skutulsfjördur
Poa alpina	Alpine meadow-grass	Naust Kirkjubólsfjall Skutulsfjördur Engidalur Skutulsfjördur
Potentilla crantzii	Alpine cinquefoil	Kirkjubólsfjall Skutulsfjördur

Latin name	English name	Location
Puccinellia distans	Common saltmarsh-grass	Kirkjuból Skutulsfjördur
Puccinellia maritima	Reflexed saltmarsh-grass	Engidalur Skutulsfjördur
Pyrola minor	Common wintergreen	Kirkjubólsfjall Skutulsfjördur Naust Kirkjubólsfjall Skutulsfjördur
Ranunculus pygmaeus	Pygmy buttercup	Kirkjubólsfjall Skutulsfjördur
Sagina subulata	Heath pearlwort	Naust Kirkjubólsfjall Skutulsfjördur Seljabrekka Skutulsfjördur
Salix herbacea	Dwarf willow	Kirkjubólsfjall Skutulsfjördur
Saxofraga cernua	Drooping saxifrage	Kirkjubólsfjall Skutulsfjördur
Saxifraga hypnoides	Mossy saxifrage	Kirkjubólsfjall Skutulsfjördur Naust Kirkjubólsfjall Skutulsfjördur
Saxifraga nivalis	Alpine snow saxifrage	Kirkjubólsfjall Skutulsfjördur
Saxifraga rivularis	Alpine brook saxifrage	Kirkjubólsfjall Skutulsfjördur
Saxifraga tenuis	Slender snow saxifrage	Kirkjubólsfjall Skutulsfjördur
Sibbaldia procumbens	Creeping sibbaldia	Kirkjubólsfjall Skutulsfjördur
Sorbus aucuparia	Rowan	Tunguskógur Skutulsfjördur
Sparganium hyperboreum	Northern burreed	Dagverdardalur Skutulsfjördur
Urtica urens	Small nettle	Hafrafell Skutulsfjördur
Utricularia minor	Lesser bladderwort	Dagverdardalur Skutulsfjördur
Vaccinium myrtillus	Bilberry	Kirkjubólsfjall Skutulsfjördur
Vaccinium uliginosum	Bog bilberry	Kirkjubólsfjall Skutulsfjördur
Veronica alpina	Alpinc speedwell	Dagverdareyri Skutulsfjördur
Veronica officinalis	Heath speedwell	Kirkjuból-Brautarholt Skutulsfjördur Tunguskógur Skutulsfjördur
Viola tricolor	Wild pansy	Tunga Skutulsfjördur

Round-leaved sundew and heath cudweed are fairly rare species. Common twayblade is on the list of protected species in Iceland (Kristinsson, 1998). It grows best in woodlands and grassy lows. The birchwoods are part of the original vegetation in Iceland and the type found here is uncommon outside Iceland and therefore has considerable protection value. It is therefore desirable to treat plants in Tungudalur gently.

An investigation into plant life in Seljalandsdalur to the north of Tungudalur (Eiríksson et al., 1998) showed that only 30-35 of the 88 species recorded in Tungudalur, Dagverdardalur and Engidalur are found there but another 90 or so different species are, none of which are as rare as the above species. In that valley, vegetation is lush and vegetation cover is generally extensive.

4.3 Fauna

No specific investigations have been carried out concerning mammals in the area but the common wild mammals in Iceland, field mouse, fox and mink can all be expected to be found there.

Birds were counted for one year at the head of Skutulsfjördur in 1991-1992 (Aegisson, 1992). Table 5 shows all the bird species in Skutulsfjördur. The number of bird species observed was 54, 3 of which were unidentified waders, but the number of individual birds was 127,750. Ducks and related birds (ducks, geese, swans) were by far the most common, followed by gulls and related birds (gulls, terns, skuas) then waders (redshank, oystercatcher, purple sandpiper, golden plover etc.) and lastly a small group of diverse species (various passerines, falcon, alcids) (see Figure 8). The most common species by far was common eider (65,434) with redshank (11,427) a poor second. The shore at the head of the fjord is an extremely viable area with an abundance of seaweed, worms, shellfish and larvae. The bird observations were made by the seashore and the birds were observed mainly feeding and resting.

TABLE 5: Bird species at the head of Skutulsfjördur 1991-1992

Latin name	English name	Total number
Cygnus Cygnus	Whooper swan	11
Alca torda	Razorbill	1
Larus glaucoides	Iceland gull	5499
Phalacrocorax carbo	Cormorant	6
Aythya marila	Scaup	39
Falco rusticolus	Gyrfalcon	2
Fulmarus glacialis	Fulmar	2
Anas acuta	Pintail	7
Anser anser	Greylag goose	265
Mergus merganser	Common merganser	6
Clangula hyemalis	Oldsquaw	2520
Anser brachyrhynchus	Pink-footed goose	2
Plvialis apricaria	Eurasian golden plover	1317
Larus ridibundus	Black-headed gull	6533
Corvus corax	Raven	56
Gallinago gallinago	Common snipe	2
Bucephala islandica	Barrow´s goldeneye	1
Larus hyperboreus	Glaucous gull	9806
Stercorarius parasiticus	Arctic skua	2
Sterna paradisaea	Arctic tern	572
Uria aalge	Common murre	1
Gavia stellata	Red-throated loon	90
Calidris alpina	Dunlin	4
Motacilla alba	White wagtail	50
Phalaropus lobatus	Northern phalarope	61
Calidris canutus	Knot	65
Anas Penelope	Wigeon	120
Rissa tridactyla	Kittiwake	2102
Crocethia alba	Sanderling	5
Charadrius hiaticula	Ringed plover	125
Chalidris maritime	Purple sandpiper	4888
Larus argentatus	Herring gull	30
Larus fuscus	Lesser black-backed gull	37
Turdus iliacus	Redwing	44
Aythya fuligula	Tufted duck	51
Catharacta skua	Greal skua	8
Numenius phaeopus	Whimbrel	3
Oenanthe oenanthe	Wheatear	3
Tringa tetanus	Redshank	11,427
Anas platynrhynchos	Mallard	6373
Larus canus	Common gull	2
Histrionicus histrionicus	Harlequin duck	44
Larus marimus	Great black-backed gull	6374
Cepphus grille	Black guillemot	2
Arenaria interpres	Ruddy turnstone	866
Haematopus ostralegus	Oystercatcher	2038
Mergus serrator	Red-breasted merganser	814
Anas crecca	Teal	11
Anthus pratensis	Meadow pipit	1
Somateria mollissima	Common eider	65,434

Latin name	English name	Total number
Somateria spectabilis	King eider	25
Scolopacidae?	Unidentified wader	1
Scolopacidae?	Unidentified wader	1
Scolopacidae?	Unidentified wader	1
		127,750

Observations over shorter periods have been made in the valleys Tungudalur (Eiríksson and Óladóttir, 1999) and Seljalandsdalur (Eiríksson et al., 1998). The following additional birds have been seen there: Redpoll (Carduelis flammea), merlin (Falco rusticolus), ptarmigan (Lagopus mutus), wren (Troglodytes troglodytes) and snow bunting (Plectrophenax nivalis). Whimbrel, common snipe, wheatear, white wagtail, redwing and meadow pipit are likely to nest in Seljalandsdalur. An overview of nesting birds in Skutulsfjördur is given in Table 6.

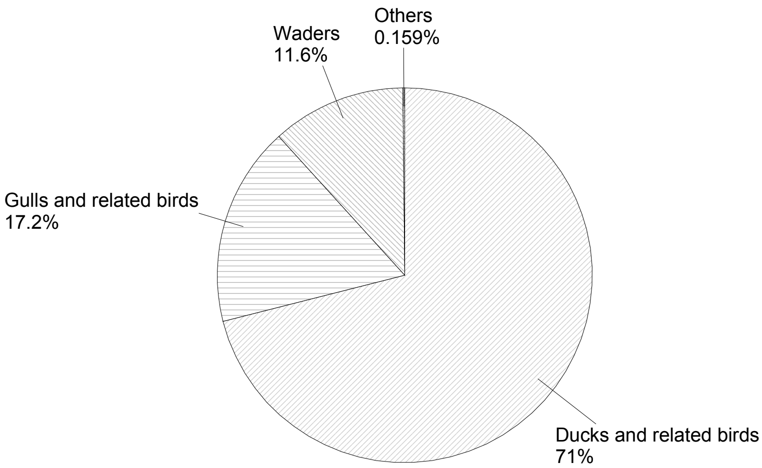

FIGURE 8: The proportion of bird types in Skutulsfjördur area

TABLE 6: Nesting birds in Skutulsfjördur (Eiriksson et al., 1998)

Latin name	English name	Nesting
Gavia stellata	Red throated loon	Confirmed
Cygnus Cygnus	Whooper swan	Confirmed
Anser anser	Greylag goose	Confirmed
Anas Penelope	Wigeon	Confirmed
Anas crecca	Teal	Confirmed
Anas platyrhynchos	Mallard	Confirmed
Aythya fuligula	Tufted duck	Confirmed
Aythya marila	Scaup	Possible
Somateria mollisiama	Common eider	Confirmed
Histrionicus histrionicus	Harlequin duck	Unknown but could nest
Clangula hyemalis	Old squaw	Confirmed
Mergus serrator	Red-breasted merganser	Confirmed
Mergus merganser	Common merganser	Unknown but could nest
Falco columbarius	Merlin	Confirmed
Falco rusticolus	Gyrfalcon	Old irregular
Lagopus mutus	Ptarmigan	Unknown but could nest
Haematopus ostralegus	Oystercatcher	Confirmed
Charadrivus hiaticula	Ringed plover	Confirmed
Pluvialis apricaria	Eurasian golden plover	Likely
Calidris maritime	Purple sandpiper	Unknown but could nest
Calidris alpina	Dunlin	Unknown but could nest
Galinago galinago	Common snipe	Likely
Numenitus phaeopus	Whimbrel	Likely
Tringa tetanus	Redshank	Confirmed
Phalaropus obatus	Northern phalarope	Confirmed
Stercorarius parasiticus	Arctic skua	Unknown but could nest

Latin name	English name	Nesting
Larus ridibundus	Black-headed gull	Confirmed
Larus fuscus	Lesser black-backed gull	Unknown but could nest
Larus marinus	Great black-backed gull	Unknown but could nest
Sterna paradisaea	Arctic tern	Confirmed
Cepphus grille	Black guillemot	Unknown but could nest
Anthus pratensis	Meadow pipit	Likely
Motacilla alba	White wagtail	Confirmed
Troglodytes troglodytes	Wren	Unknown but could nest
Oenanthe oenanthe	Wheatear	Likely
Turdus iliacus	Redwing	Likely
Corvus corax	Raven	Confirmed
Plectrophenax nivalis	Snow bunting	Likely

4.4 Climate and meteorology

Climate data have been collected from the three nearest weather stations, in Sudureyri (1.1961-7.1989), Bolungarvík (8.1994-4.2001) and Aedey (1.1961-7.1989) (Icelandic Meteorology Office, 2001). Sudureyri is within the study area and lies to the west. Bolungarvík is to the northwest and fairly close. Aedey is located to the northeast of the area. Table 7 shows the annual mean climate data from these three stations. There is a big difference between the three stations. The mean annual temperature at Sudureyri is 3.4˚C, 0.5˚C higher than Aedey 2.9˚C. The annual mean maximum temperature is 5.4-5.9˚C. The total annual precipitation at Sudureyri which is the highest among the three stations is 1117.1 mm, but lowest at Aedey just 606.2 mm. It is clear that there is a difference between west and east of the study area.

TABLE 7: Mean annual weather data from Sudureyri, Bolungarvík and Aedey

Item	Sudureyri (1.1961-7.1989)	Bolungarvík (8.1994-4.2001)	Aedey (1.1961-7.1989)
Mean annual temperature (˚C)	3.4	3.1	2.9
Mean annual max temperature (˚C)	5.9	5.8	5.4
Mean annual min temperature (˚C)	1.0	0.5	0.8
Highest annual temperature (˚C)	18.4	19.5	17.4
Lowest annual temperature (˚C)	-13.4	-13.2	-13.5
Mean annual total precipitation (mm)	1117.1	719.8	606.2
Mean annual relative humidity (%)	82.8	83.6	89.3

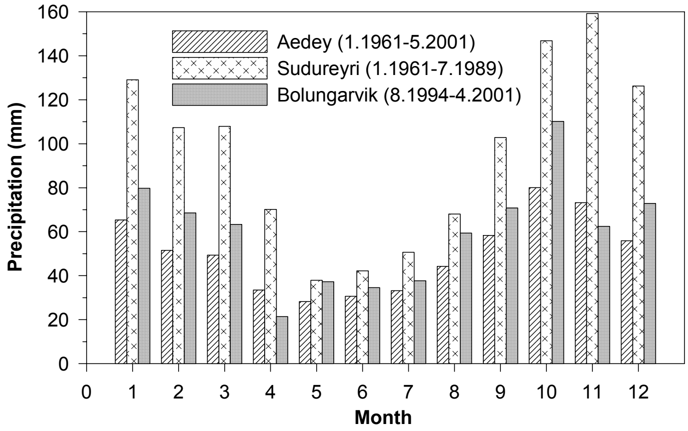

FIGURE 9: Monthly precipitation at Aedey, Sudureyri and Bolungarvík

4.4.1 Precipitation

Precipitation was gauged at the Aedey, Sudureyri, Bolungarvík meteorological stations. Figure 9 shows monthly precipitation at the three stations. At Sudureyri the maximum precipitation is in November, 160 mm, the minimum in May, about 37.9 mm. At Bolungarvík the maximum is in October, 110.2 mm, the minimum in April, about 21.4 mm. At Aedey the maximum is in October, 80.1mm, the minimum in May, about 28.2 mm.

4.4.2 Temperature and humidity

Temperature data for the three meteorological stations are shown as monthly average temperatures in Figure 10. At Sudureyri the mean maximum temperature is in July, about 17.4˚C, and mean minimum temperature in January, about -10.8˚C. At Bolungarvík the mean maximum temperature is in July about 18.9˚C, and mean minimum temperature in February, about -12.5˚C. At Aedey the mean maximum temperature is in July, about 16.7˚C, and mean minimum temperature in March, about -10.9˚C.

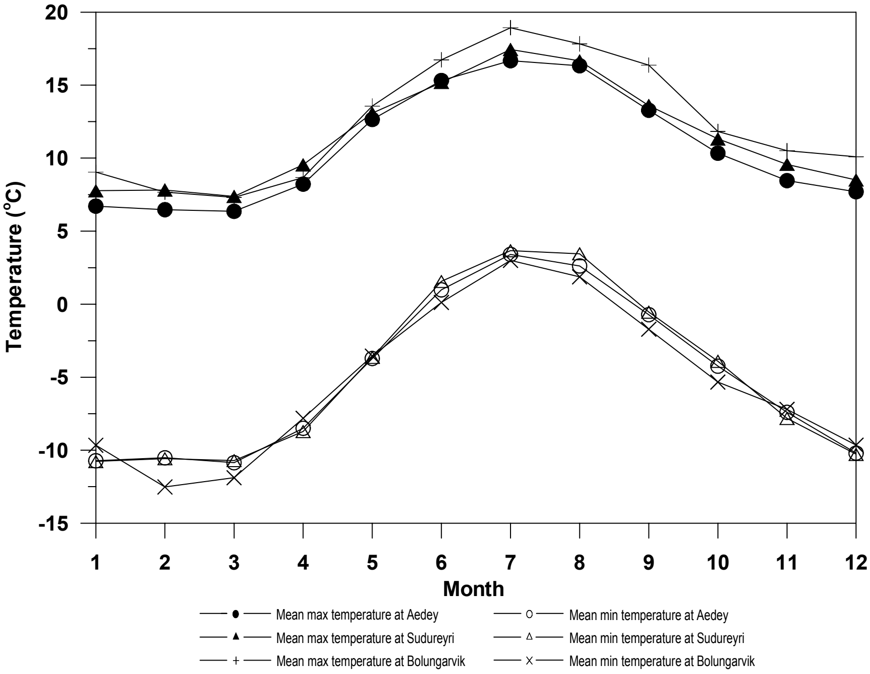

FIGURE 10: Monthly temperatures at Aedey, Sudureyri and Bolungarvík

Humidity in this area is generally high due to high precipitation. Mean monthly relative humidity data from the three stations is shown in Figure 11. There is less difference in the monthly humidity at the three stations, ranging from 74.4% to 84.8%.

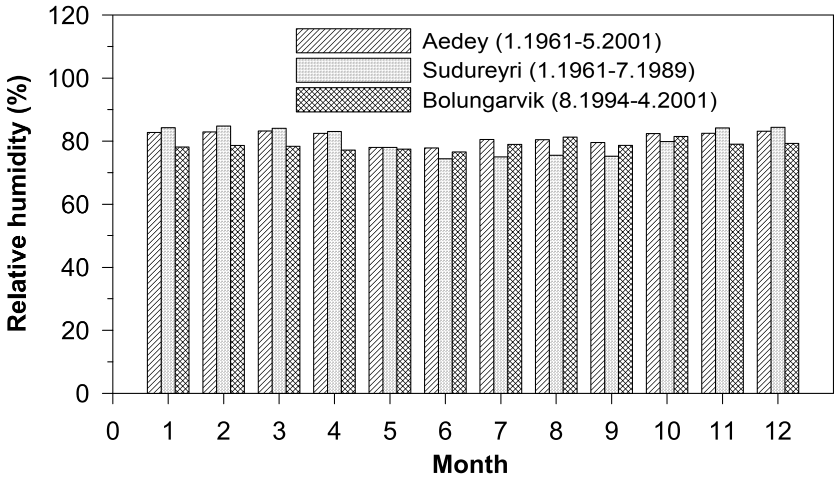

FIGURE 11: Mean monthly relative humidity at Aedey, Sudureyri and Bolungarvík

4.4.3 Wind patterns

Wind conditions are also measured at Sudureyri, Bolungarvík and Aedey. Monthly average wind directions were noted to make a wind rose plot, and it is seen that the most common wind directions are northeasterly. The greatest average wind speed at Sudureyri and Bolungavík is about 7.5 m/s, while at Aedey it reaches near 14 m/s. Figure 12 shows the monthly wind direction and wind speed at the three stations.

4.5 Geothermal water

Besides samples from well LA-02, sampled in 1998, a few samples were collected from the old gradient wells drilled in 1975-1978. Silica only was analyzed in two samples, one from well H-4 and one from a gradient well. Both show silica content of about 75 ppm. The chemical composition of the well water samples is presented in Table 8. The quality of the geothermal water is good and it can be used directly.

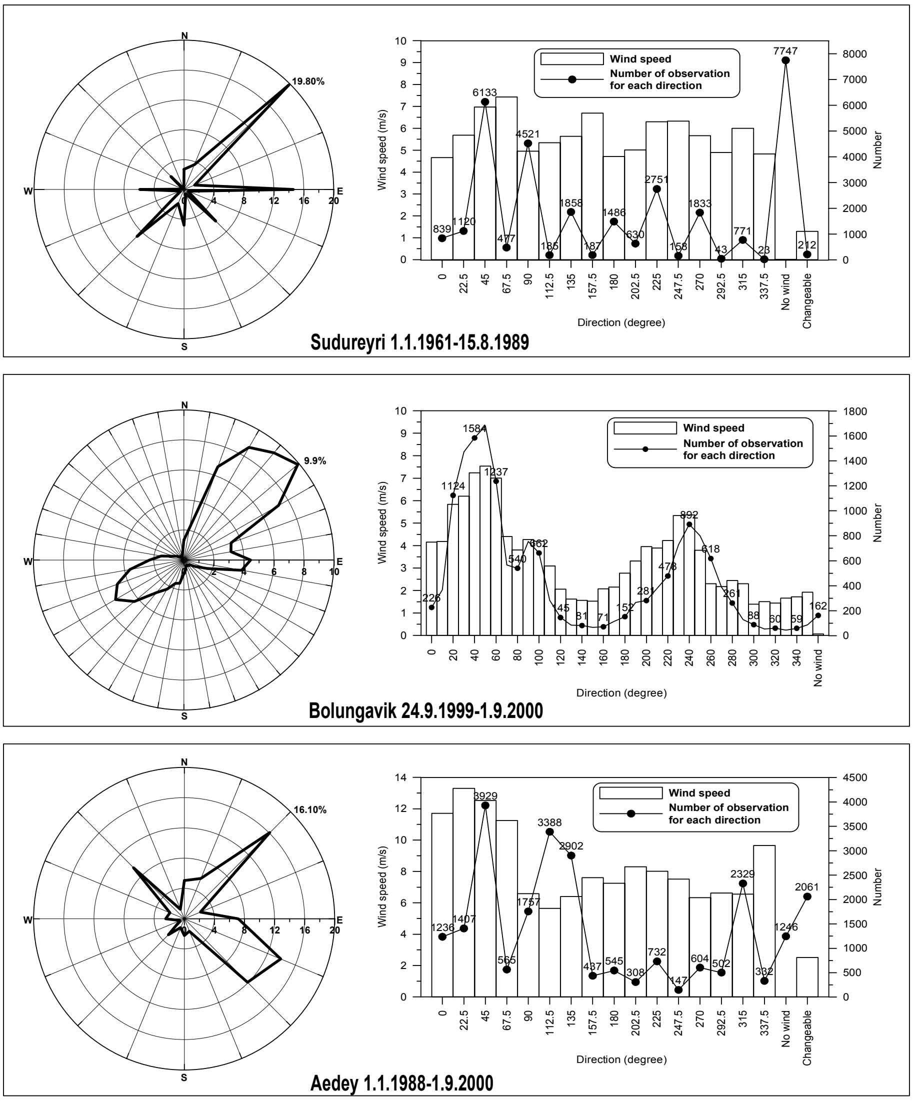

FIGURE 12: Frequency of wind directions and mean wind speed for each direction at Sudureyri, Bolungarvík and Aedey

4.6 Socio-economics

Ísafjardarbaer community includes a town and three villages, which are Ísafjördur, Flateyri, Thingeyri and Sudureyri. Total population is 4278 (Statistic Iceland, 2000). Ísafjördur, which is the "capital" of the West fjords, is located in the northeast part of the Ísafjardarbaer area. Ísafjördur town has a long history and has for a long time been one of the largest fishing industry centres in Iceland (Iceland Travel Information, 2001).

Cultural life has flourished in Ísafjördur through the ages and still does. The regional library was founded in 1889 and Iceland's first music school was established in 1911. A secondary grammar school was opened in 1970 and now has a branch in nearby Patreksfjördur. There is also a newly founded art school in Ísafjördur, bearing the name of Iceland's first architect, Rögnvaldur Ólafsson, not to mention the art gallery Slunkaríki, one of the smallest yet most noteworthy galleries in the country, mounting exhibitions all year round. The West-Fjords Folk Museum has a remarkable collection of traditional tools and relics.

TABLE 8: The chemical composition of well water samples (mg/l)

Location	**Laugar**	**Tungudalur**				
Sample	LA-02	H-2	H-2	H-2	H-2	H-3
Date	1998.03.31	75.12.01	76.09.05	77.08.21	78.12.16	78.12.15
Temperature (˚C)	64.4	25	26.9	24.8	64	66
PH/˚C	9.74/23.4	9.61/21	9.9/19	9.87/20	9.5/24	9.3/23
CO_2	9.06	7.8	9.6	11.6	17.5	20
H_2S	0	<0.1	<0.1	<0.1	<0.1	<0.1
SiO_2	60.9	59	59	58	60	55
B	0.06					
Na	90.61	90.2	90.3	96.9	96.9	239
K	0.88	0.5	0.6	0.5	0.45	2
Mg	0.11	<0.1	<0.1	0.1	0.1	0.05
Ca	8.7	3.2	4.2	3.4	3.47	91.31
F	0.41	2.17	1.92	1.75	1.49	0.29
Cl	56.7	77.8	77.4	79.6	81.3	382
SO_4	78.08	55.1	53.4	64.6	68.4	189.1
Al	0.045					
Mn	0.0005					
Fe	0.0082					
TDS	390	319	327	358	339	1047
δD (‰SMOW)	-81.4					
$\Delta^{18}O$ (‰SMOW)	-11.59					

Industry in Ísafjördur has always been at the forefront of Iceland's enterprises. The Ásgeirsverslun trading company, which also controlled fishing ships and fish processing, was in its heyday, the biggest and most powerful business enterprise in the country. Ísafjördur was a pioneer in canning and shrimp fishing in Iceland. The fishing industry in Ísafjördur is still second to none, but demands change with the times. Thus, one of the leading companies of high technology electronics for the fishing industry is now to be found in Ísafjördur.

Sudureyri is a small and peaceful fishing village. Many small boats are equipped and sail from Sudureyri, characterising the village, especially during the summer. Hot water is in the ground at Laugar near Sudureyri and is used to heat buildings and houses and provides water in the local swimming pool, which is the only outdoor thermal pool in the area and very popular. Flateyri is a small village located at the north side of Önundarfjördur and Thingeyri is the oldest trading centre in the western part of the area.

5. ENVIRONMENTAL IMPACTS OF DEVELOPMENT

5.1 Land use

Land is required during the different geothermal development stages. These operations will modify the surface morphology of the area. During drilling, land is required for rig installation, access roads, drill pads, steam lines and transmission lines. The drill pad area ranges from 300-500 m^2 for a small truck-mounted rig, to 1200-1500 m^2 for a small to medium rig. Installation of the pipelines that will transport the geothermal fluids, and the construction of the utilization plants, will also affect the surface morphology and the scenic view.

The amount of land that is disturbed by road construction during geothermal development can be quite large (Brown, 1995); about 12 hectares are estimated for road construction alone when 15 wells are drilled. In general, the terrain of this area is steep and access difficult. Furthermore, such an environment may also have severe erosional problems. Road construction in these steep situations normally involves extensive intrusion into the landscape and can often cause slumping or landslides with consequent loss of vegetation. The lack of vegetation can then cause greatly accelerated erosion with the possibility of further slumping or landslides. This is a sparsely vegetated relatively inaccessible region, which is almost devoid of vehicle tracks. The weather is frequently inclement. Winter snowfall is heavy and the snow lingers far into the summer. Therefore, road construction in this area is difficult, stabilization of the roads in such an environment is difficult and land affected by development is correspondingly increased.

5.2 Vegetation and wildlife

In low-temperature geothermal fluid there is generally a smaller quantity of harmful chemicals than in high-temperature fluid, so its effect on the vegetation and wildlife is usually negligible. The impact on vegetation and wildlife is mainly due to land use during geothermal development. During drilling and plant operation the land is disturbed or changed to accommodate other uses; natural habitats for wildlife and plants are either destroyed or altered. This kind of impact cannot be prevented, but with careful project planning, direct-heat facilities (wells, distribution systems, access roads and end-use facilities) may be sited to avoid unusual or unique habitats and critical habitats for endangered species.

5.3 Air quality

Geothermal fluids typically contain various non-condensable gases (e.g., hydrogen sulfide) and other components (e.g. mercury, arsenic, boron) many of which cause rather serious environmental problems for geothermal development. For example CO_2 is a so-called greenhouse gas that can cause global temperature to rise, and hydrogen sulfide is toxic to humans. But low-temperature geothermal fluid in this area contains very little boron, no gaseous CO_2, no hydrogen sulfide, mercury, nor arsenic. So it would not affect air quality during geothermal development. And the small amount of CO_2 present is dissolved so that no gaseous emissions are expected. Of course, certain emissions are inevitable during well drilling and flow testing, but such activities are of short duration and usually do not result in serious long-term environmental degradation.

5.4 Water quality

During drilling or flow-tests, undesirable bentonite with the frequent addition of other substances harmful to the environment should be treated and separated from the liquid after use. The water can be reutilized but the solid matter, along with drill cuttings, should be stocked in special waste tanks or ponds. Wells should be cased when groundwater is struck. The impact on the environment caused by drilling mostly ends once drilling is completed.

During plant operation, the most serious water-quality concern is that geothermal fluids released to natural aquatic bodies will degrade water quality and result in negative impacts to fish and other aquatic organisms. However, the low-temperature geothermal fluids used in most direct-use applications generally contain low levels of chemicals and the discharge of spent geothermal fluids is seldom a problem. Such fluids can usually be discharged into surface water after cooling. The water can be cooled in special storage ponds or tanks to avoid modifying the ecosystems in natural bodies of water. At the same time, a loop system to avoid or minimize equipment failure resulting in accidental releases of fluids to aquatic bodies, has been designed for direct-use projects.

5.5 Subsidence

Extraction of large quantities of geothermal fluids from underground aquifers may give rise to subsidence, i.e. a gradual sinking of the land surface. This is an irreversible process. The actual incidence of subsidence depends on the nature of the reservoir and the surrounding geologic formations in fracture permeable reservoirs. In sedimentary reservoirs, subsidence could be a substantial problem. Subsidence may be reduced through a well-planned program of injection of geothermal fluids. Moreover, such injection also conserves the geothermal resource and extends the reservoir production life. Subsidence is a relatively slow process, but over a number of years the lowering of the land surface may reach detectable levels, in some cases, on the order of a few tens of centimeters and even meters, and should be monitored systematically.

5.6 Noise

During low-temperature geothermal development, noise is usually a problem only during well-drilling/testing activities adjacent to residential areas, recreational areas and critical breeding areas for certain wildlife (1-1/2 miles or approximately 1 km). Typical noise levels for drilling in high-temperature areas are (Hunt, 2001):

- Air drilling -120 dBa (85 dBa with suitable muffling);
- Discharging wells after drilling (to remove drilling debris) - up to 120 dBa;
- Well testing - 70-110 dBa (if silencers are used);
- Heavy machinery (earth moving during construction) - up to 90 dBa;
- Well bleeding - 85 dBa (65 dBa if a rock muffler is used);
- Mud drilling - 80 dBa;
- Diesel engines (to operate compressors and provide electricity) - 45-55 dBa if suitable muffling is used.

Proper siting of facilities can minimize noise problems. However, the noise generated in direct heat applications is usually negligible.

5.7 Socio-economic impacts

Even with large-scale geothermal developments for electric power production, negative socio-economic impacts have usually been quite small. Therefore, negative socio-economic impacts from large-scale direct-heat applications are also likely to be small or negligible. Archaeological resources may be disturbed during geothermal development activities. The simplest way to avoid such disturbances is to conduct thorough archaeological surveys of prospective development areas and to locate facilities in non-problem areas. Hot-spring areas, especially, were sometimes favoured as pioneer sites of settlements.

6. RISK

6.1 Exploration and development risk

The utilization of a geothermal reservoir carries a significant risk in low-temperature geothermal development. A complete understanding of the reservoir can only be obtained by withdrawing fluids from the reservoir over a sustained period, with subsequent computer modeling to assess the performance in the future. It can take several years of production before the reservoir performance can be gauged with confidence since the reservoir rate of decline is frequently exponential in nature with high initial rates of decline.

Assessment of resource size and production capacity (resource assessment) is a critical part of any geothermal development. At the feasibility stage without long-term production data, resource assessments rely on the extent of the reservoir as defined by drilling and geophysical anomalies, and knowledge of reservoir fluid temperatures. Large errors are inherent in such assessments.

Once long-term reservoir performance has been established, the production capacity will be estimated in terms of MW of energy over a particular time period (commonly taken as 30 years). Such estimates reduce the likelihood of excessive withdrawal of fluids from reservoirs, which leads to reservoir pressure decline and reduced well (energy) output. Reservoir pressure decline may in turn allow low-temperature groundwater to flood the system and cool the reservoir even further. The risk of pressure decline can be mitigated by conservatively sizing the rate of heat extraction in comparison to the estimated resource capacity.

Once a resource has been developed, regular monitoring of production data (engineering and scientific data) is undertaken, accompanied by simulation studies to better predict the future behaviour of the reservoir in order to maximize production and minimize premature reservoir failure.

6.2 Snow avalanches

Snow avalanches are a familiar natural hazard in the north, east and west of Iceland. It endangers the security of residents and facilities. Figure 13 shows some avalanche villages and towns in Iceland. The West-fjords are in the old basaltic rock formations, 3-16 million years old, and have been eroded by glaciers during periods of glaciation. The fjords are embraced by steep mountains, which reach a height of approximately 600-800 m above sea level. Plateaus above the slopes exist in most areas in the West-fjords, and huge amounts of drifting snow may be transported on the plateaux and collected in the slopes and especially the gullies. In the past big avalanches have taken place in Ísafjördur and Flateyri, killing people and damaging many summerhouses. In April 1994 an avalanche struck a skiing area and summer cottages in Ísafjördur, killing one person. In October 1995 an avalanche fell on the village Flateyri, killing 20 people (Haraldsdóttir, 1999). So for geothermal development in these places, the possible effect of avalanche accidents should be considered.

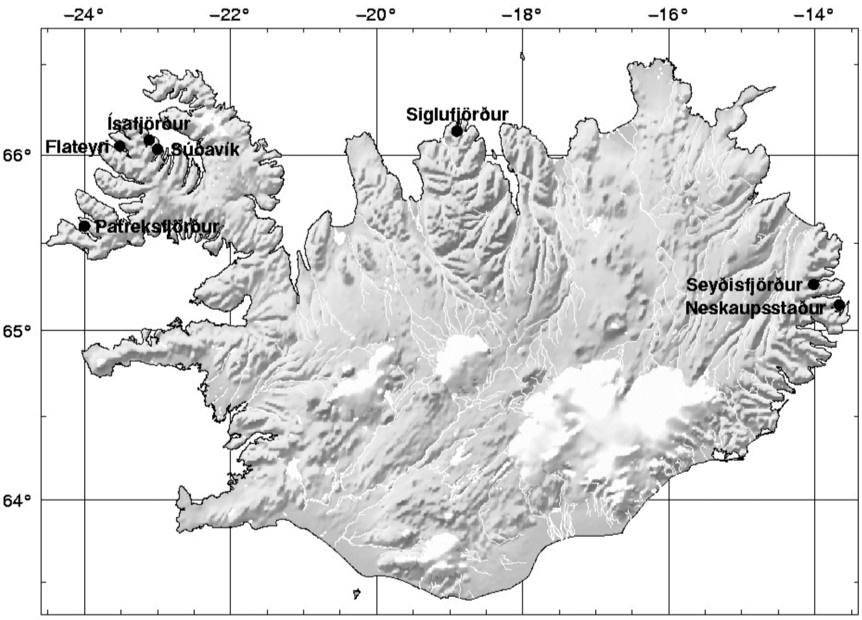

FIGURE 13: Some villages and towns in Iceland, where there is high risk for snow avalanches

7. MONITORING

7.1 Reasons for monitoring (Hunt, 2001)

1. To obtain data from which rational and informed management decisions can be made by developers and regulatory authorities;
2. To verify that management decisions are having the desired outcomes;
3. To enable the public to have confidence in the environmental management process;
4. To assist in building up a knowledge of geothermal systems and how to develop them in an environmentally responsible way.

7.2 Monitoring subsidence

Ground subsidence can be measured by repeat leveling using traditional optical survey techniques. Permanent survey marks (benchmarks) are installed on the ground or on permanent structures such as concrete pipeline supports. The elevation of these is then measured, relative to a base station outside the field, using standard 2nd or 3rd order techniques along closed loops. Temporary intermediate points are generally needed. In areas of high subsidence rate (> 100 mm/yr) the leveling needs to be completed quickly to avoid introducing errors caused by ground movement between the start and closure of a loop. The frequency of surveys will depend on the rate of subsidence and the location of the subsidence area.

7.3 Monitoring groundwater changes

7.3.1 Groundwater level

Variations in water level in a shallow unconfined groundwater aquifer can easily be measured in shallow monitoring holes. These holes are about 3-5 cm in diameter and are generally drilled vertically using a small truck-mounted auger. The depth depends on the depth down to the water table, and needs to extend 5-10 m deeper than the natural water table. The hole should not be situated in a topographic low that might become flooded, close to roads, or within the grout screen area of a deep production well. The holes should be solid cased (PVC or similar) in the vadose zone, and slotted or screened casing used from the water table to the bottom. In places where the ground temperature is less than about 50˚C, plastic (PVC or ABS) casing can be used, but for higher ground temperatures steel casing should be used. The open area of the screened casing should approximate the natural porosity of the rock formation, and the slots should widen inwards to minimize plugging by fine formation material. A record should be kept of the casing pattern, and the position and elevation of the hole should be established by surveying. It is likely that over a long period of time, fine silt and debris will migrate through the screened casing and be deposited in the bottom of the hole. The casing should extend 10-20 cm above the ground surface and the top closed by a locking cap to prevent children dropping stones etc. into the hole or people using it as a water well. In fields with high gas content, there should be a small hole in the cap to allow the escape of gas entering the well through the screened casing. The wellhead also needs to be indicated by a marker post and protected from damage by vehicles or animals. Where possible, the well should be at or close to a gravity monitoring benchmark. Measurement of the water level can be made using a simple electric circuit device powered by a small battery. Alternatively, a water level recorder, which comprises a pressure transducer coupled to a data-logger set to record every hour can be installed.

7.3.2 Groundwater temperature

The temperature of groundwater can easily be measured in groundwater monitoring wells using a digital thermometer and a probe. Where possible, the temperature should be measured not only at the water surface but also deeper in the monitoring well, to enable a temperature profile in the water to be obtained. The same equipment should be used for all measurements and the wires between the thermocouple sensor and the instrument should not contain any joints.

7.3.3 Groundwater chemistry

Samples for laboratory analysis are best obtained from groundwater monitoring wells after water level and temperature measurements have been made. Samples should not be collected from stale and stagnant water in these wells; only after 5-10% of the well-bore volume of water has been removed and naturally replaced should a sample be collected. Removal of stagnant water and collection of the sample are generally done using a small portable electric pump.

Important parameters that should be determined are: pH, chloride, lithium, sodium, potassium, calcium magnesium, sulphate (SO_4), total silica (SiO_2), boron, total bicarbonate (HCO_3) and fluoride. In addition, determinations of stable isotopes ^{18}O, d^2H, and tritium are worthwhile making.

7.4 Monitoring reservoir mass changes

Generally developers routinely measure the amount of mass withdrawn from, and reinjected into, the field. However, these measurements do not provide information about natural mass losses from thermal features or natural recharge. Changes in mass can be determined from microgravity monitoring at selected points.

7.5 Monitoring reservoir chemistry changes

Withdrawal of deep reservoir fluid generally induces recharge, which may alter the chemistry of the fluid, especially if a significant proportion of the recharge water has a very different chemistry.

If the recharge fluid is a non-mineralised non-geothermal groundwater, or an acid-sulphate water and a bicarbonate water that are low in chloride, then a reduction in chloride content of the reservoir liquid may occur in the discharge from wells in areas near where the invasion occurs. Monitoring of the dilution trends can provide information about the rate of lateral movement of the invasion front. However, if the field is adjacent to the ocean and seawater is drawn in, then the chloride concentration may increase. From a suite of chemical species it is generally possible, using a mixing diagram, to determine the amount of mixing of the various components.

7.6 Monitoring climatic conditions

In order to assess the influence of variations in climatic conditions on thermal features, and groundwater temperatures and levels, it is also necessary to measure rainfall, air temperature and air pressure. These can generally be obtained from a weather observatory installed near the plant. In the early stages of development it is generally necessary to install several small weather observatories, in and around the geothermal field, to collect information.

8. CONCLUSIONS

- The possible geothermal area is thought to be a low-temperature area, the geothermal water temperature is expected to be below or around 70°C and the water suitable for direct use. Probable development includes space heating and a swimming pool.
- Environmental impact of geothermal development in this area is small and mainly during the drilling stage. The impacts are: surface disturbances; negative effects on vegetation and wildlife due to land use, and noise; subsidence caused by fluid withdrawal may possibly be added. Careful planning can reduce these negative impacts.
- This geothermal system is expected to be a fracture-dominated geothermal system and the reservoir narrow. There are no surface geothermal manifestations, so there is high risk in geothermal development. The risk of snow avalanche accidents in this area is considerable. Either the development site should be at a distance from possible avalanche locations or security measures should be taken.

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